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ABSTRACT OR SUPPORTING INFORMATION

Aerothermal Effects of Cavities and Protuberances for High-Speed Sample Return Capsules

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Introduction:

Extraterrestrial sample return is a growing component of solar system exploration. Currently, four missions, Stardust,1 Muses-C,2 Genesis, and Mars Sample Return, are under development that employ sample return as a prime component of the mission architecture. Respectively, these missions will return samples from the tail of a comet, an asteroid, the solar wind, and, Mars. An important component of these missions and the focus of this paper is the design of the sample return capsule (SRC).

The purpose of the SRC is to safely return to Earth any gathered samples for terrestrial analysis. The two major design constraints for any SRC are as follows: 1) it must be able to survive a high-speed Earth entry (11 km/s to as a high as 15 km/s), 2) the mass of the SRC must be as small as possible. Because the SRC mass is carried from Earth to the sample sight and back, the SRC mass is a strong driver in the mission mass budget. Further, for the Mars Sample Return Capsule, planetary protection is another constraint. For this capsule, the probability of planetary contamination at Earth due to an SRC failure at entry must be minimal.

For an SRC, a possible failure mechanism is severe local heating as a result of cavities and or protuberances in the SRC forebody heatshield. For example, the Apollo Command Module had a number of cavities and protuberances as part of the baseline design;3 Wind-tunnel tests of models containing small cavities and protuberances showed severe local heating augmentations in the vicinity of these surface discontinuities.4-5 As another example, the Genesis SRC forebody heatshield contains penetrations (cavities) to mount the vehicle to the carrier bus. It is expected that these penetrations will also experience a severe local heating environment. A concern is that the large thermal gradients may produce sufficient thermal stress to cause local mechanical failure of the heatshield.

Penetrations to the forebody heatshield can also result from damage at vehicle integration, during launch, or during transportation of the sample return capsule from earth to the sample site and back. For example, the Stardust SRC was damaged near the shoulder during the heatshield integration process producing a local surface discontinuity. Also, the Stardust SRC traverses through the tail of a comet and is in space for 7 years. Thus, damage to the heatshield as a result of micrometeroid impact is a concern.

Finally, it is difficult to characterize the effects of these potential heatshield singularities with ground-test facilities. Either detailed simulation or a dedicated flight test is required.
For example for Apollo, a flight experiment was conducted to determine the effects of heatshield singularities.3 In the report's introduction it says:

It was recognized that this problem (heatshield singularities) could not be investigated and resolved with any degree of confidence in ground facilities alone; hence, at the request of the NASA Manned Space Craft Center, the present investigation was initiated to provide an intermediate step between ground tests and Apollo flight tests utilizing a Pacemaker launch vehicle.

The purpose of this paper is to assess the impacts of local cavities and protuberances on SRC forebody heatshield performance. To achieve this objective, the local heating environment around various surface discontinuities will be characterized employing numerical flow simulations for typical SRC entry conditions. The surface heating distributions will be used to perform thermal stress simulations within the forebody heatshield material.

Procedure:

The governing equations and flow modeling applicable to the high speed entry problem in this work have been described in detail in Refs. 1,6,7. Surface heating predictions during entry are obtained from laminar, nonequilibrium, reacting, axisymmetric Navier-Stokes flow simulations. Thermal and mechanical stresses within the TPS will be evaluated using a methodology developed for the X-33 metallic TPS analysis by Kontinos, et. al.[8,9]. Details of the methodology will be described in the final paper.

Initial Results:

To show the effects of a simple forebody penetration, a high-fidelity, laminar, axisymmetric flow calculation using the methodology employed for the Stardust heatshield[1,6,7] design is generated with and without a simple penetration for the Genesis heatshield geometry; the Genesis heatshield design contains three penetrations near the shoulder to connect the SRC to the carrier bus. When the SRC separates from the carrier bus for Earth entry, three cavities remain in the heatshield.

The geometry and trajectory information used in this analysis are shown in Figs. 1 and 2. The vehicle is a 60 degree sphere-cone with 1.5 m base diameter. The relative entry velocity and entry angle are respectively 10.7 km/s and 10 degrees. Peak heating occurs at an altitude of 58 km and a velocity of 9.5 km/s. A penetration profile used for this analysis is shown in Fig. 1. The penetration is 1.905 cm (.75 inches) long and .5 cm deep parabola.

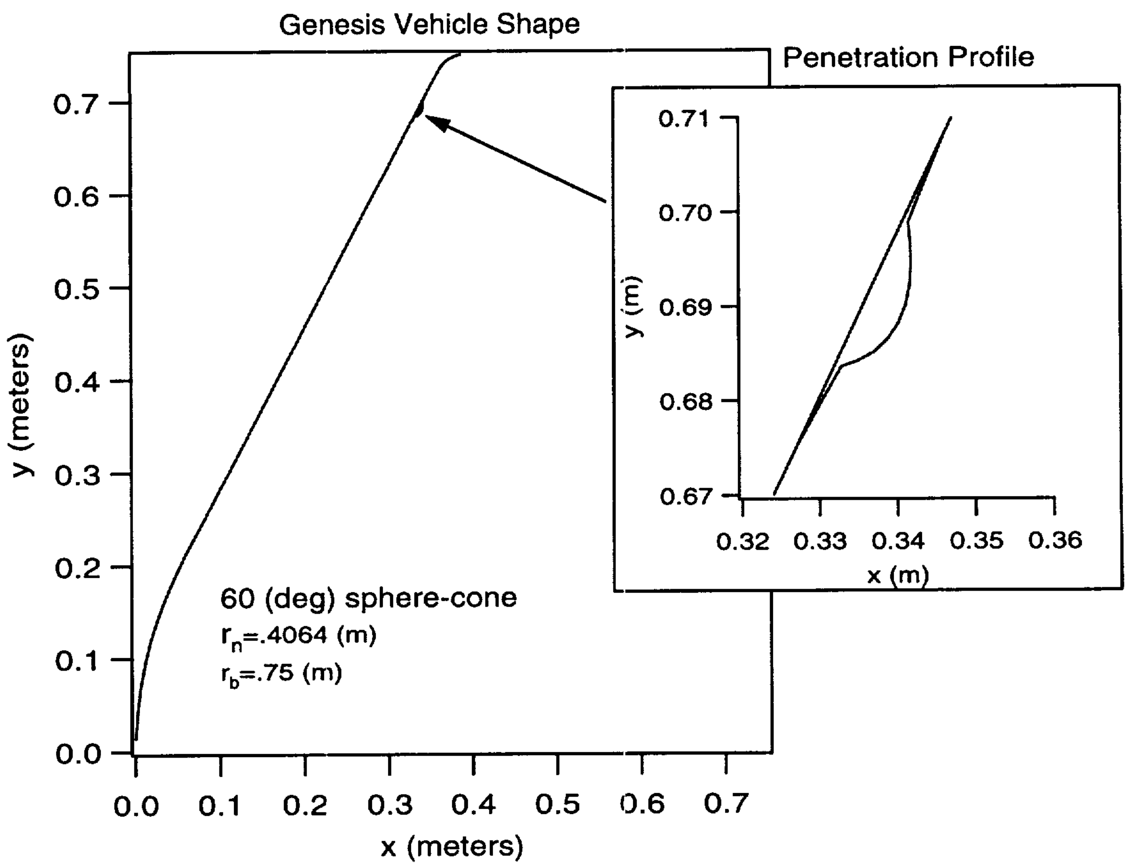
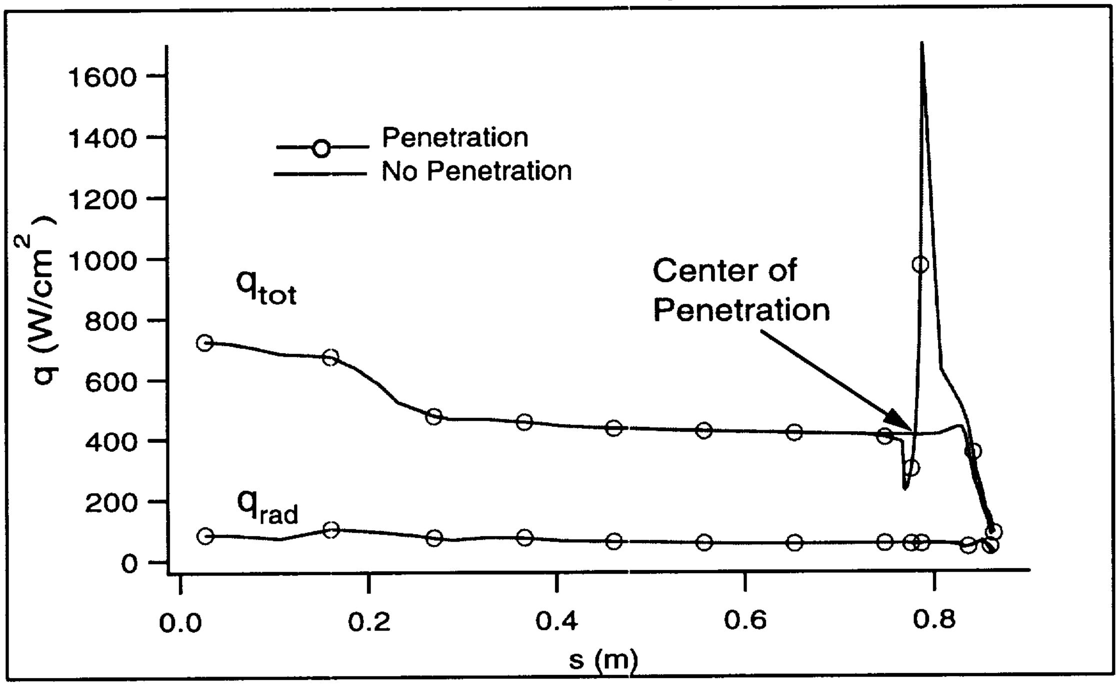


Fig. 1: Geometry and Penetration Profile for Heating Calculation

The results of the heating analysis are shown in Fig. 2. The curves are representative of heating calculations with and without the penetration as shown in Fig. 1. It is seen that the introduction of the forebody penetration introduces a large increase in the heat flux over a very short distance. The increased heating is over twice the stagnation heating value. Further, the large increase in heating occurs in the region of maximum aerodynamic shear. The large increase in heating occurs because the flow separates over the front lip and then reattaches on the back lip of the penetration. The thinning of the boundary layer at the reattachment point causes the increase in heating. A major concern is that the sharp thermal gradients will introduce severe mechanical stress into the material producing a local heatshield failure at the penetration location. Further, the fluid-material interaction involving the conditions of maximum aerodynamic shear combined with high heating and large thermal gradients will be difficult or impossible to reproduce in an arc-jet or any test facility.

These results are consistent with wind-tunnel experiments performed for the design of the Apollo Command Module in the NASA LaRC Mach 8 hypersonic tunnel.[5] Small models with depressions to model recessed shear and compression pads were tested. The wind-tunnel tests indicated maximum heating levels of 3-4 times the stagnation value on the down-stream lip of the recession with significant increases in heating downstream of the penetration. The current simulation predicts only a factor of two increase in heating over the stagnation value at the down-stream lip of the penetration. Further grid resolution, however, in the current simulation will likely produce a higher heating value at the penetration location.

Genesis Heating Calculation
with and without a Forebody Penetration



<u>Entry Interface Conditions</u>

Relative Velocity=10.7 km/s, Mass=200 kg, Entry Angle= 10 (deg)

<u>Peak Heating Conditions</u>

V=9.5 km/s, Alt= 58 km

Fig. 2: Axisymmetric Laminar Heating Calculation using GIANTS

Summary:

A large local increase in heating resulting from a cavity on the Genesis forebody heatshield is predicted from the analysis in this abstract. This large local increase in heating may produce large thermally induced mechanical stresses within the material and potentially local heatshield failure. For the full paper, thermal stress analyses will be generated for penetrations of varying sizes and locations on the Genesis heatshield. Further, thermal and fluid analyses will be generated for candidate geometries applicable to the Mars sample return capsule heatshield design with varying types of penetrations.

References:

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